Effect of Temperature and Moisture on Quinclorac Soil Half-life and Resulting Native Grass and Forb Establishment

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Quinclorac will control leafy spurge and not injure many established native grasses and forbs. Seeding of desirable species is often required to reestablish native vegetation after an invasive weed-management program, but quinclorac residue may inhibit the reestablishment of native species. Greenhouse studies were conducted to estimate quinclorac dissipation rates in Northern Great Plains soils and the effect of residue on establishment of some native grass and broadleaf plants. Quinclorac 50% dissipation time (DT_{50}) ranged from > 21 to 112 d in four soils from the Northern Great Plains. The quinclorac DT_{50} was dependent on several factors including soil type, moisture content, temperature, and especially organic matter (OM). Across four different soil textures, quinclorac dissipation generally increased as soil moisture content increased, but moisture had less of an impact in low OM soils. Quinclorac dissipation also increased as temperature increased in the four soils. The most rapid dissipation occurred in soils with higher OM (> 6%), with an average DT_{50} of < 38 d, at 45% moisture content, held at 16 C. Wild bergamot, purple coneflower, blanketflower, and stiff goldenrod seedling growth were all reduced by quinclorac residue at 6 μg kg^{-1}, the lowest concentration evaluated in the study. The native grass species big bluestem, intermediate wheatgrass, and switchgrass generally were tolerant of quinclorac, but green needlegrass was sensitive, and seedling growth declined as quinclorac residue increased from 6 to 375 μg kg^{-1}. Based on a quinclorac application of 840 kg ha^{-1} and 150 frost-free d, seeding of sensitive forbs and grasses should be delayed at least 12 mo after herbicide application.

Nomenclature: Quinclorac; leafy spurge, *Euphorbia esula* L.; wild bergamot, *Monarda fistulosa* L.; big bluestem, *Andropogon gerardii* Vitman; blanketflower, *Gaillardia aristata* Pursh; green needlegrass, *Nassella viridula* (Trin.) Barkworth; intermediate wheatgrass, *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey; purple coneflower, *Echinacea purpurea* (L.) Moench; stiff goldenrod, *Oligoneuron rigidum* (L.) Small var. *rigidum*; switchgrass, *Panicum virgatum* L.

Key words: Dissipation, invasive species, seeding native species, soil residual.

Quinclorac was first registered as a soil- or foliar-applied herbicide for annual grass and broadleaf weed control in 1992 (Sterling et al. 1995). Quinclorac has been used in a variety of settings, such as control of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] in rice (*Oryza sativa* L.), crabgrass (*Digitaria* spp.) in turf, and field bindweed (*Convolvulus arvensis* L.) in chemical fallow (Grossmann 1998; Street and Mueller 1993). Quinclorac can be used to control leafy spurge (*Euphorbia esula* L.) in pasture, rangeland, and wildlands (Kuehl and Lym 1997) and will not injure most native and cultivated grass species (Enache and Ilnicki 1991; Manthey et al. 1990).

Quinclorac has a narrow activity spectrum. For instance, in a six-state regional trial, quinclorac applied to control leafy spurge did not injure leadplant (*Amorpha canescens* Pursh), purple prairie clover (*Dalea purpurea* Vent.), red clover (*Trifolium pratense* L.) in Nebraska, prairie wild rose (*Rosa arkansana* Porter), sandbar willow (*Salix interior* Rowlee), anemone (*Anemone* spp.) in North Dakota and wild raspberry (*Rubus* spp.) in Minnesota (Lym et al. 1997). In addition, quinclorac did not harm the western prairie fringed orchid (*Platanthera praeclara* Sheviak & Bowles) because plants treated with quinclorac regrew as vigorously and were as fecund as nontreated orchids (Erickson et al. 2006).

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Management Implications

Quinclorac can be used to control leafy spurge in pasture, rangeland, and wildland, with the added benefit of having little effect on most established native forbs and grasses. Seeding of native species is often desirable in a long-term invasive weed-management program, but these programs can fail if a herbicide is not used to control the target weed or other nondesirable species before seeded species establishment. However, herbicide residue can also result in reduction of desired species establishment and density. Quinclorac soil half-life (DT_{50}) ranged from > 112 to 21 d in four soils from the Northern Great Plains. The quinclorac DT_{50} was dependent on several factors, including soil type, moisture content, temperature, and especially organic matter. Across four different soil textures, quinclorac dissipation generally increased as soil moisture content increased, but moisture had less of an effect in low organic matter soils. Based on the results of this study, between 140 and 190 g ha^{-1} quinclorac could remain 12 mo after application at 840 g ha^{-1} and a growing season of 150 frost-free d. Wild bergamot, purple coneflower, blanketflower, and stiff goldenrod seedling growth were all reduced by quinclorac residue at 6 μg kg^{-1}, the lowest concentration in the study. The native grass species big bluestem, intermediate wheatgrass, and switchgrass generally were tolerant of quinclorac but green needlegrass was sensitive, and seedling growth declined as quinclorac residue increased from 6 to 375 μg kg^{-1}. Landmangers that apply quinclorac for leafy spurge control should not plan to reseed the treated area until at least 12 mo after application or longer in low organic matter soils or cold conditions.

The use of quinclorac to control leafy spurge was largely developed in the 1990s, but the herbicide was little used until a grazing label was obtained in 2010 (EPA 2010). Although control of leafy spurge with quinclorac has been well documented (Kuehl and Lym 1997; Lamoureux and Rusness 1995), the environmental fate of the herbicide when used in noncropland sites is generally unknown. What little has been published concerning quinclorac soil persistence appears contradictory. Quinclorac 50% dissipation time (DT_{50}) in a Lethbridge sandy clay loam was 48 wk, with persistence tied to soil moisture conditions (Hill et al. 1998). In contrast, quinclorac half-life was reported as 22 to 23 d in soil of growing tobacco (*Nicotiana tabacum* L.) (Chen et al. 2007). Elsewhere, quinclorac half-life has been reported from 18 to 176 d (EPA 2007).

Control of invasive species does not always result in reestablishment of desirable native plants (Almquist and Lym 2010; Samuel and Lym 2008). Seeding desired species after weed control can improve long-term restoration (Mangold et al. 2015). However, mortality of newly seeded species can be high during the first or second year after seeding (Mangold 2012), which can allow rapid reinvasion of the targeted weed. To prevent reinvasion by a target weed, land managers often use herbicides both before and after establishment of newly seeded species (DiTomaso 2000; DiTomaso et al. 2007; Lym and Tober 1997; Wirt and Lym 2016). However, herbicide residue can also result in reduction of the establishment and density of desired species (Aldrich 2002; Jacobs et al. 2007).

Knowing the dissipation rate of quinclorac is important if pasture, rangeland, or wildlands are seeded after a weed-control program using this herbicide. The objective of this research was to (1) evaluate the effect of temperature and moisture on soil dissipation of quinclorac in soils found in the Northern Great Plains, and (2) determine the effect of quinclorac residue on newly seeded native forbs and grasses. The overall goal was to more-accurately estimate the postapplication time required for seeding of native species in previously treated areas.

Materials and Methods

The effect of moisture and temperature on the dissipation of quinclorac was evaluated on four soils found in the Northern Great Plains. Fargo silty clay (fine, smectitic, frigid Typic Epiaquerts) (Soil Survey Staff 2011), Svea-Barnes loam (fine-loamy, mixed, superactive, frigid Pachic Hapludolls and fine-loamy, mixed superactive, frigid Calcic Hapludolls), Glendive-Havre clay (coarse-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents and fine-loamy, mixed, superactive, calcareous, frigid Aridic Ustifluvents), and Lamoure loamy sand (fine-silty, mixed, superactive, calcareous, frigid Cumulic Endoaquolls) soils were collected near Fargo, Jamestown, Medora, and Walcott, ND, respectively (Table 1). Soil was obtained from the 0- to 15-cm (5.9 in) depth, screened through a 6-mm (0.2-in) sieve, air dried for 5 d, and stored at 22 C (71.6 F) until needed (approximately, 1 to 2 mo). Field capacity (FC) was determined by weight for each soil type in a preliminary study (Conklin 2012).

Moisture Study. Quinclorac was applied at 1,000 μg kg^{-1} (1.6×10^{-5} oz lb^{-1}) in 10 ml (0.34 oz) of solution to 500 g (17.65 oz) of air-dried soil in wax-paper bags and allowed to dry for 24 h. Soil was mixed in the bags by inverting 20 times and poured into individual 10-cm diam by 8-cm, plastic pots. Pots had five 0.25-cm diam holes predrilled in the bottom, which had been covered with filter paper. Each pot was placed in a separate 13- by 13- by 4-cm deep tray to collect possible leachate, and soil-water contents were established at 22.5, 45, or 90% field capacity by weight. Pots were placed in incubators without lights and with covers placed loosely over the pot to allow air exchange without excessive drying. Four pots of each soil type were removed 0, 2, 4, 8, and 16 wk after treatment (WAT). The desired FC was maintained by weighing pots twice weekly and adding water to the surface as needed. Upon removal,

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Table 1. Physical and chemical characteristics of four soils from the Northern Great Plains included in the soil dissipation experiment.

Location	Soil series	Sand	Silt	Clay	Organic matter	Field capacity gravimetric water content	pH
		% by wt					
Fargo	Fargo	5	45	50	7.0	55	7.2
Jamestown	Svea-Barnes	37	42	21	6.4	51	5.7
Medora	Glendive-Havre	5	35	60	1.2	38	8.1
Walcott	Lamoure	86	9	5	2.6	49	7.8

the soil was frozen to reduce or eliminate microbial activity until the bioassay. Soil with water contents of 22.5% and 45% FC was warmed 5 d at 16 ± 2 C. Soil with a water content of 90% FC was allowed to warm 2 d at 16 ± 2 C and 3 d at 21 ± 2 C to reduce water content to approximately 45% FC. The soil in each pot was individually mixed before planting.

Quinclorac concentration remaining in the soil was determined by a sunflower (*Helianthus annuus* L.) bioassay. A standard curve with four replications per treatment of each soil type was prepared with quinclorac concentrations of 0, 31, 62, 125, 25 0, 500, and 1,000 μg kg^{-1} of soil. The soil was air dried, mixed, and placed into plastic pots, as previously described. Eight Nuseed (Breckenridge, MN) X48391 sunflower seeds were planted 1 cm deep into each pot of soil. Soil was moistened by adding water alternately to the surface and subsurface throughout the bioassay as needed to maintain approximately 50% FC. After emergence, sunflowers were thinned to four per pot, and water soluble fertilizer (Jack's Classic All Purpose Water Soluble Plant Food, 20–20–20 [N–P–K], J. R. Peters, Inc., 6656 Grant Way, Allentown, PA 18106) was applied at 85 kg nitrogen ha^{-1} (75.8 lb ac^{-1}). Pots were rotated every 4 d to reduce environmental variability in the greenhouse. The greenhouse was maintained at 21 C, and natural sunlight was supplemented with metal halide lights with an intensity of 450 μE m^{-2} s^{-1} for a 16-h photoperiod. Common sunflowers were cut at the soil surface 15 to 17 d after planting, dried at 40 C for 48 h, and dry weight was compared with a standard curve to estimate quinclorac concentration.

Temperature Study. Soil was weighed, mixed, and placed in pots, as previously described, except water content was maintained at 45% FC for the duration of the temperature study. The soil was stored in dark chambers with temperature held constant at 8 ± 2, 16 ± 2, or 24 ± 2 C. Four pots of each soil type were removed, as previously described, and frozen until the sunflower bioassay was initiated. Soil was warmed to 16 ± 2 C for 5 d and then placed in the greenhouse and prepared for planting. The moisture and temperature bioassays were conducted at the same time and used the same standard curve.

Seeding study. The effect of quinclorac residue on seedling establishment of native forbs and grasses was evaluated in a greenhouse study. Svea-Barnes loam was used in all greenhouse studies because soil properties and quinclorac DT_{50} results were the intermediate of the soils evaluated. Quinclorac at concentrations of 0, 6, 12, 23, 47, 95, 188, and 375 μg ae kg^{-1} in 10 ml of water was pipetted onto 300 g of soil in a serpentine manner. The soil was then air-dried for 24 h and thoroughly mixed, placed in pots (same size as in persistence studies), and brought to 50% moisture capacity, as previously described. Native grass species evaluated included big bluestem (*Andropogon gerardii* Vitman) 'Bison', green needlegrass [*Nassella viridula* (Trin.) Barkworth] 'Lodorm', intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey] 'Manifest', and switchgrass (*Panicum virgatum* L.) 'Dacotah'. Kentucky bluegrass (*Poa pratensis* L.) 'Kenblue' was included because the species has tolerance to quinclorac (EPA 2013). Native forb plants included wild bergamot (*Monarda fistulosa* L.), blanketflower (*Gaillardia aristata* Pursh), purple coneflower [*Echinacea purpurea* (L.) Moench], and stiff goldenrod [*Oligoneuron rigidum* (L.) Small var. *rigidum*]. Native grass seed was obtained from U.S. Department of Agriculture–National Resources Conservation Service, Plant Materials Center (Bismarck, ND) and the forbs from local collections taken the summer and fall before the study. Seed of each species was overplanted and thinned to eight plants per pot.

Grass species were grown 4 to 6 wk and forbs were grown 8 to 12 wk in a greenhouse at a maintained temperature of approximately 24 C with a 16-h photoperiod of natural and supplemented light using a halide light with an intensity of 450 μE m^{-2} s^{-1}. Plants were watered as needed and fertilized once with a diluted 20–20–20 (N–P–K) nutrient solution as previously described. Plant material

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Table 2. Effect of moisture on quinclorac dissipation to 50% (DT_{50}) in four soils from the Northern Great Plains 112 d after treatment with 1,000 μg kg^{-1} held at 16 C.

	Soil series[a]			
Moisture content	Fargo	Glendive-Havre	Lamoure	Svea-Barnes
% Field capacity	DT_{50}			
22.5	74 ± 8 b	> 112[b] b	94 ± 11 b	67 ± 3 b
45	32 ± 3 a	34 ± 13 a	61 ± 5 a	39 ± 6 a
90	24 ± 2 a	78 ± 10 b	50 ± 8 a	45 ± 4 a
R^{2c}	0.98	0.87	0.89	0.97

[a] Numbers followed by the same letter within each soil series are not significantly different according to probability of difference ($P \geq 0.01$).
[b] Actual DT_{50} exceeded the sensitivity of the test; however, means were separated using the estimated value.
[c] R^2 values from the equation for the standard curve used in each soil series to estimate herbicide concentration.

was harvested, dried at 50 C for 96 h, and weighed to estimate quinclorac effect on production.

Data Analysis. The moisture and temperature studies were a randomized complete block with four replicates. Sunflower stem height was analyzed with SAS (Statistical Analysis Software 2003, version 9.1, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513) ANOVA using PROC GLM. Experiments were conducted twice from late-October until mid-March. Runs were homogeneous and data were combined. Regression analysis (PROC CORR) was used to develop curves based on sunflower stem height from standard curve soils.

The time to DT_{50} of quinclorac was calculated individually for each replicate in every soil. The first-order rate Equation 1 was used to describe quinclorac dissipation (Walker 1987):

$$\ln(A_t/A_o) = -kt \quad [1]$$

where A_t was the concentration of quinclorac in the soil at time t, A_o was the initial quinclorac soil concentration, and k was the dissipation rate constant. Equation 2 was used to calculate the DT_{50}:

$$DT_{50} = 0.693/k \quad [2]$$

where k was the rate constant from Equation 1.

When the DT_{50} value for a replicate could not be determined because it was > 112 d (16-wk length of the study), the value was considered missing. A DT_{50} value of 112 d was used when four or more values were missing within one treatment. The DT_{50} values of quinclorac in each soil were subjected to ANOVA and compared using least-squares means. Treatment means were separated by the probability of difference ($P \leq 0.05$).

The seeding-study experiment was a randomized complete-block design with four replicates and was repeated (two runs). Each species was analyzed as a separate experiment. Plant growth weights were initially analyzed with the PROC GLM procedure in SAS software (SAS Institute, Cary, NC) to determine homogeneity of the error mean squares from the two runs. Data from individual runs were combined by species and were analyzed with the PROC REG statement in SAS software to estimate the relationship between the independent variables (quinclorac concentration) and the dependent variable (dry weight). Based on some of the linear results ($P < 0.05$), it appeared that a linear relation might not be the best option for explaining the response of some species to quinclorac, so quadratic and cubic terms were used in the model. The SAS PROC STEPWISE statement was used to determine which independent variables should be included in the model at $P < 0.05$. If none of the independent variables were retained in the model, it was assumed there was no relationship between the dependent and independent variables.

Results and Discussion

Moisture Study. The effect of moisture on quinclorac dissipation was dependent on soil type but was generally more rapid at 45% and 90% FC than it was at 22.5% FC in all soils evaluated (Table 2). The quinclorac DT_{50} at 22.5% FC was > 112 d in Glendive-Havre clay soil but declined to 34 d at 45% FC. The decline in DT_{50} was less dramatic in the Lamoure loamy sand, which averaged 94 and 61 d at 22.5% and 45% FC, respectively. Within a soil type, quinclorac dissipation was similar at 45 and 90% FC, except the Glendive-Havre clay soil, in which DT_{50} increased from 34 to 78 d as soil moisture increased from 45 to 90% FC.

These findings are in general agreement with Hill et al. (1998), who reported quinclorac dissipation in a Leth-

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Table 3. Effect of temperature on quinclorac dissipation to 50% (DT_{50}) in four soils from the Northern Great Plains 112 d after treatment with 1,000 μg kg^{-1} and held at 45% field capacity moisture.

	Soil series[a]			
Temperature	Fargo	Glendive-Havre	Lamoure	Svea-Barnes
C	DT_{50}			
8	64 ± 7 b	60 ± 14 a	> 112[b] b	41 ± 9 b
16	35 ± 1 a	45 ± 19 a	68 ± 7 b	45 ± 5 b
24	21 ± 4 a	53 ± 3 a	45 ± 5 a	21 ± 3 a
R^2[c]	0.95	0.93	0.92	0.88

[a] Numbers followed by the same letter within each soil series are not significantly different according to probability of difference ($P \geq 0.01$).

[b] Actual DT_{50} exceeded the sensitivity of the test; however, means were separated using the estimated value.

[c] R^2 values from the equation for the standard curve used in each soil series to estimate herbicide concentration.

bridge sandy clay loam was slowest in very dry conditions (3 driest yr on record, 113 mm) and increased as soil moisture increased to wet (precipitation greater than normal, 246 mm), but dissipation slowed in the very wet regime (3 wettest yr on record, 375 mm). However, quinclorac DT_{50} was 48 wk under normal moisture (212 mm) in the Lethbridge soil compared with only 42 d at 45% FC when averaged over the four soil types in this study (Table 2). The reason for the large difference in DT_{50} was due, in part, to the experimental design. The Lethbridge study was conducted under field conditions with simulated rainfall from June through September, but the DT_{50} included the winter months when the soil was frozen.

Quinclorac is degraded by microbes in the soil (Shaner 2014), so as soil moisture increased, biological activity also increased, resulting in a shorter half-life. The only exception was the Glendive-Havre soil, in which DT_{50} more than doubled from 34 to 78 d as moisture increased from 45 to 90% (Table 2). The increase may be explained by the low OM (OM) of 1.2% in the Glendive-Havre soil, the lowest in the study (Table 1). Quinclorac is readily bound to the organic carbon in the soil and has a high relatively K_{oc} (soil organic carbon–water partition coefficient) of 446 (Hill et al. 2000). Consequently, the Glendive-Havre soil would have contained more nonbound quinclorac than the other soils in this study, and as the soil reached near anaerobic conditions, microbial breakdown likely decreased.

Temperature Study. Quinclorac DT_{50} values generally decreased as temperature increased, but the rate of change depended on the soil type (Table 3). Quinclorac DT_{50} values were lowest in the Svea-Barnes loam and decreased from 41 to 21 d as the soil temperature increased from 8 to 24 C. Quinclorac DT_{50} was longest in the Lamoure loamy sand with > 112 d at 8 C but declined to a DT_{50} of 45 d at 24 C.

Soil OM is the main constituent involved in binding quinclorac (Sterling et al. 1995) and may be indicative of soil half-life. In these studies, the DT_{50} averaged over all moisture and temperature regimes was 42 and 43 d, respectively, for the Fargo clay (7% OM) and Svea-Barnes loam (6.4% OM) soils, compared with an average of 59 and 72 d for the Glendive-Havre clay (1.2% OM) and Lamoure sandy loam (2.6% OM), respectively (Tables 2 and 3). Soil pH was not indicative of quinclorac half-life because the soils with the shorter average half-life—Fargo clay and Svea-Barnes loam—had a pH of 7.2 and 5.7, respectively. The Lethbridge clay loam, which had quinclorac half-life of 48 wk, also had a low OM content of 2% (Hill et al. 1998).

Quinclorac soil mobility has been correlated with soil OM. The amount of quinclorac that leached declined by 20% as soil OM increased from 2.7 to 5.9% in Alberta, Canada, soils (Hill et al. 2000). Quinclorac leaching also decreased in very sandy soils (> 80%) as the OM increased (Adams and Lym 2015).

Quinclorac can be applied for weed control in noncrop and grazing land at ≤ 840 g ai ha^{-1}, which is the most commonly used rate for leafy spurge control in the Northern Great Plains. Based on the results of this study, at between 140 and 190 g ha^{-1} (0.125 and 1.70 lb ac^{-1}) of quinclorac (highest and lowest OM soil), the quinclorac could remain 12 mo after application with a 150 frost-free d growing season.

Seeding Study. Quinclorac reduced the growth of all seedling forbs, whereas most grass species evaluated were tolerant (Figures 1 and 2). Wild bergamot, purple coneflower, blanketflower, and stiff goldenrod seedling growth were all reduced by quinclorac residue at 6 μg kg^{-1},

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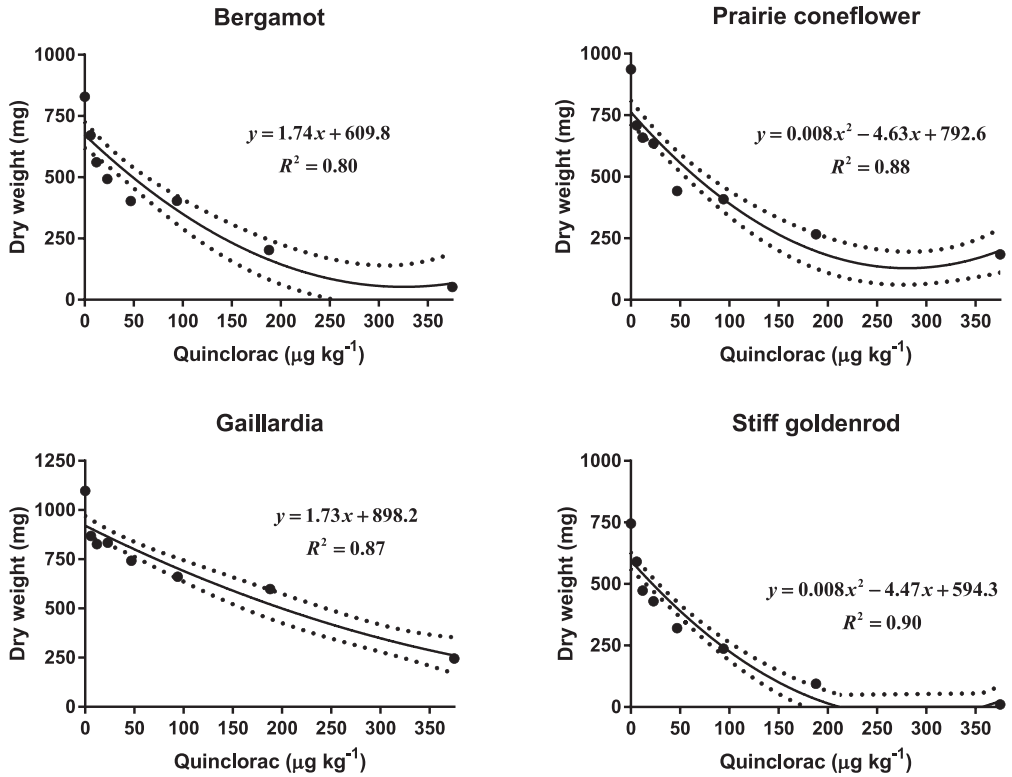

Figure 1. The effect of quinclorac soil residue from 0 to 375 µg kg^{-1} on seedling growth of four native forb species grown in the greenhouse for 8 to 12 wk ($P < 0.05$ for all data). Dashed lines represent 95% confidence interval bands of the main effect.

the lowest concentration in the study (Figure 1). Growth of all forbs generally declined as quinclorac concentration increased, and few stiff goldenrod plants survived quinclorac at 375 µg kg^{-1}. These results are consistent with a field study in which quinclorac was applied to established plants in Georgia (Corley 1995). Blanketflower cover was reduced 90 and 100% after quinclorac was applied at 560 (0.5 lb ac^{-1}) and 1,120 g ha^{-1}, respectively, whereas purple coneflower injury averaged 70%, and no plants flowered. In the same study, cornflower (*Centaurea cyanus* L.) and blackeyed-susan (*Rudbeckia hirta* var. *pulcherrima* Farw.) were not injured at either quinclorac application rate (Corley and Murphy 1994), again illustrating that land managers must consider both the herbicide used and the desired species to be seeded in long-term management programs.

All cool- and warm-season grasses evaluated were more tolerant of quinclorac than were the forb species (Figure 2). Seedling growth of intermediate wheatgrass, switchgrass, and Kentucky bluegrass were unaffected by quinclorac, even at 375 µg kg^{-1}. The tolerance of Kentucky bluegrass to quinclorac was expected because this herbicide is labeled for weed control in sports turf, golf courses, etc., which grow this species (EPA 2013). Switchgrass was also tolerant to quinclorac at 280 or 560 g ha^{-1} applied preemergence, and biomass was enhanced in a three-state, regional field study (Mitchell et al. 2010). These results are in contrast to a trial in the Pacific Northwest, in which quinclorac applied at 560 g ha^{-1} reduced switchgrass production when applied both during the year of establishment and 1 yr later (Boydston et al. 2010).

Big bluestem appeared tolerant to quinclorac in visual evaluations, but growth declined slightly as herbicide concentrations increased (Figure 2). However, green needlegrass was very sensitive to quinclorac, and growth declined rapidly as herbicide concentration increased (Figure 2). Green needlegrass growth declined by 58%, compared with the control plants, at quinclorac concentrations of 375 µg kg^{-1}.

The susceptibility of green needlegrass to quinclorac was not expected because this grass is listed as tolerant to quinclorac on the use label (EPA 2013). However, application is restricted to mature plants after harvest. Big bluestem, Kentucky bluegrass, and switchgrass mature plants were also considered tolerant to quinclorac and were tolerant as seedlings in this study as well.

Certain cool and warm season grasses can be seeded 0 to 7 d after quinclorac application at rates of up to 840 g ha^{-1}, but application to Kentucky bluegrass is not allowed for at least 28 d after emergence (EPA 2013). The time interval for seeding both grass and forb species has not been

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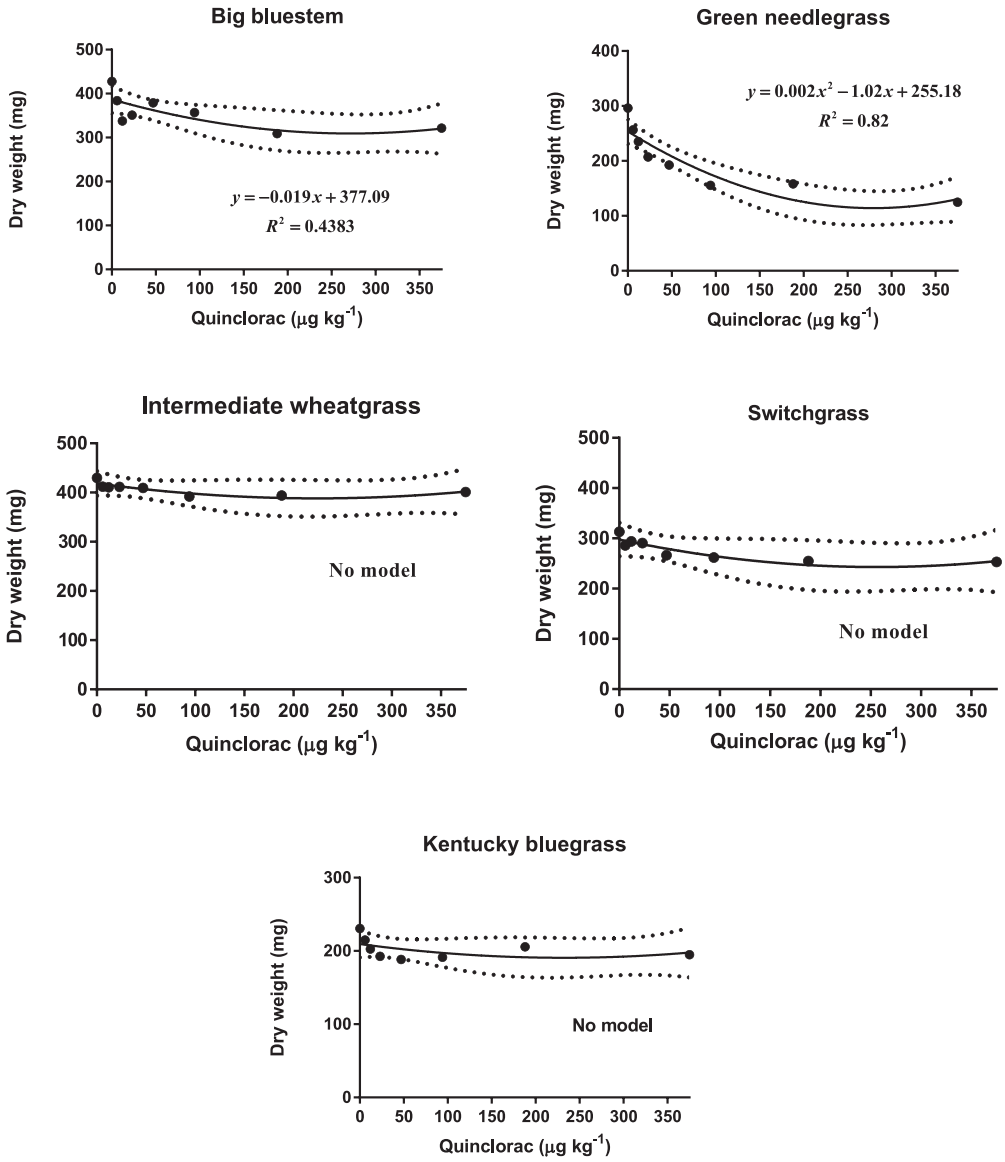

Figure 2. The effect of quinclorac soil residue from 0 to 375 µg kg^{-1} on seedling growth of four native grass species and Kentucky bluegrass grown in the greenhouse from 4 to 6 wk. In the case of three grass species, there was no model that explained variation in dry weight by herbicide concentration, that is, no herbicide effect. $P < 0.05$ for all data. Dashed lines represent 95% confidence interval bands of the main effect.

published for wildland sites. Jacobs et al. (2007) noted some forb species were reduced by quinclorac treatments in only one of two experimental runs in the greenhouse and speculated that environmental conditions or a slight variation in herbicide rate or both might change species sensitivity. Plant sensitivity may also vary by soil type and competitive stress.

Implications. Quinclorac soil half-life in the Svea-Barnes soil used in the seedling study ranged from 67 to 21 d (Tables 2 and 3). Based on a quinclorac application of 840 g ha^{-1} and 150 frost-free d, approximately 210 to 6.5 g ha^{-1} or 104 to 0.03 µg kg^{-1} of the herbicide would remain 12 mo after treatment (calculated with a soil bulk density of 1.35 g cm^{-3} [0.79 oz in^{-3}] and 15 cm depth). Switchgrass and intermediate wheatgrass would likely be tolerant of quinclorac at 104 µg kg^{-1}, but big bluestem could be injured, and green needlegrass would likely be severely injured at that concentration (Figure 2). All forbs evaluated in this study would be severely injured at the maximum, estimated concentration of 104 µg kg^{-1} but would likely survive at concentrations of < 1 µg kg^{-1}

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(Figure 1). Plant injury would likely be much greater if the soil has low OM, such as the Glendive-Havre or Lamoure soils (Table 1), which also resulted in the maximum quinclorac half-life (Tables 2 and 3). These studies confirm the possible quinclorac persistence in the soil for extended periods, even longer than the well-documented herbicide picloram (Mabury and Crosby 1996).

Land mangers who apply quinclorac for leafy spurge control should not plan to seed the treated area until at least 12 mo after application, based on the results of this study. The time before seeding to avoid herbicide injury may increase under dry and or cold conditions. For examples, quinclorac applied at 300 g ha^{-1} reduced faba bean (*Vicia faba* L.) seeded plants the following year, ranging from 100% in very dry conditions to 80% in very wet soils (Hill et al. 1998). The data for this study were obtained in a controlled environment, and plants in the wild could be even less tolerant to quinclorac residue because of harsh environmental conditions and competition from other species. However, similar research with aminopyralid applied to native forbs in the greenhouse gave similar tolerance estimates for species also tested in the field (Mikkelson and Lym 2013). Even though quinclorac generally will not injure many broadleaf and grass species when applied to established plantings, the long soil residual will delay seeding of many forbs and some grasses in a reestablishment program.

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